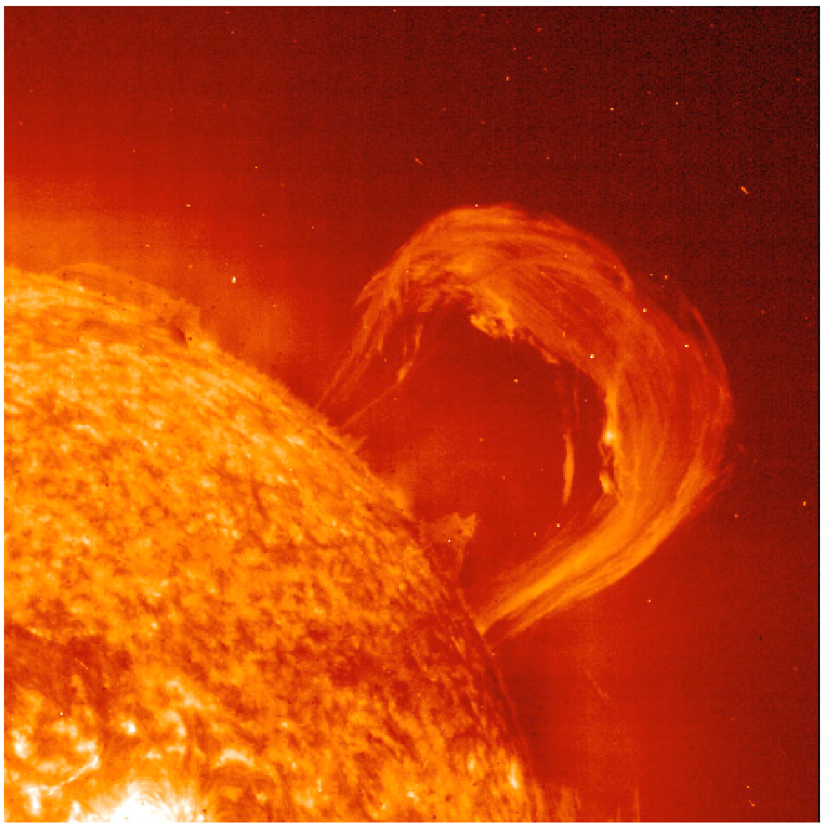
Outflows & the Circumnuclear Environment of Accreting Supermassive Black Holes

Tahir Yaqoob (JHU/GSFC)



Collaborators:

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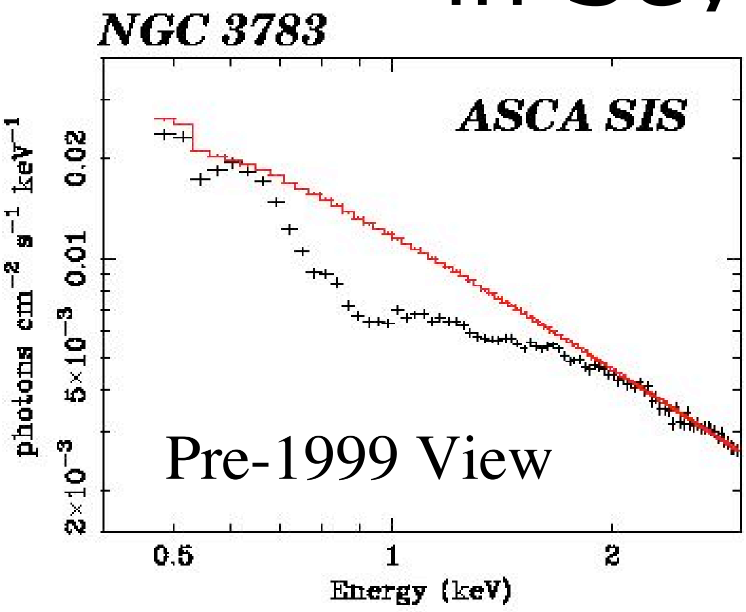
X-ray Absorption in Ionized Gas in Seyfert 1 Galaxies



- Before Chandra & XMM, CCDs had best spectral resolution (FWHM ~30,000 - 10,000 km/s in soft X-rays, 7,500 at Fe-K energies).
- ~50% of Sy 1 known with complex (likely photoionized) X-ray absorption.
- Individual O edges claimed but could have been confused.
- Chandra & XMM gratings, with FWHM down to ~300 km/s, revolutionalized study of “warm absorbers”, wealth of complexity, unresolved absorption lines, some emission lines.

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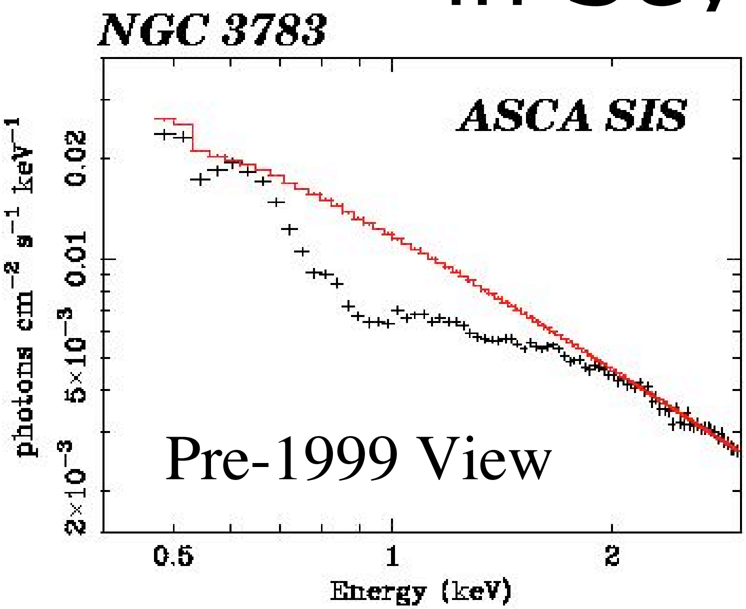

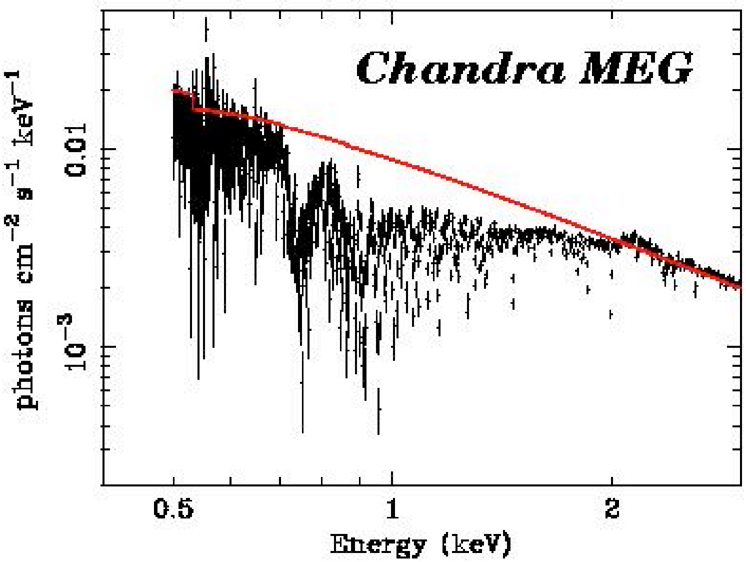

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Velocity Resolution & Effective Area

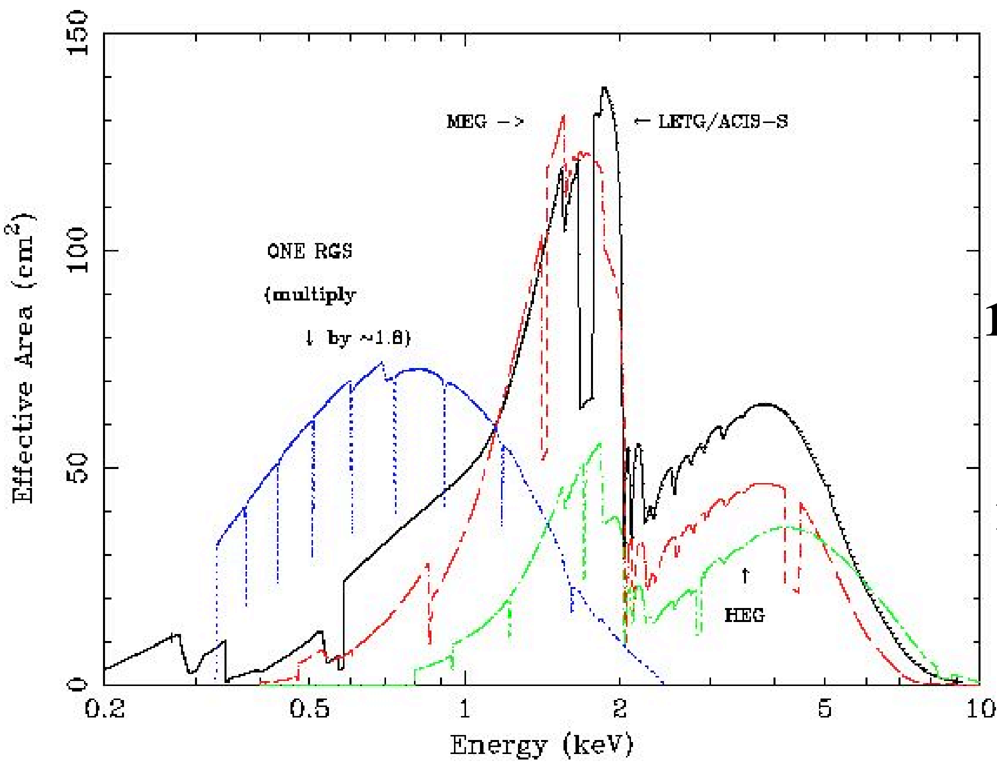
Gratings:
best resolution at lowest energies

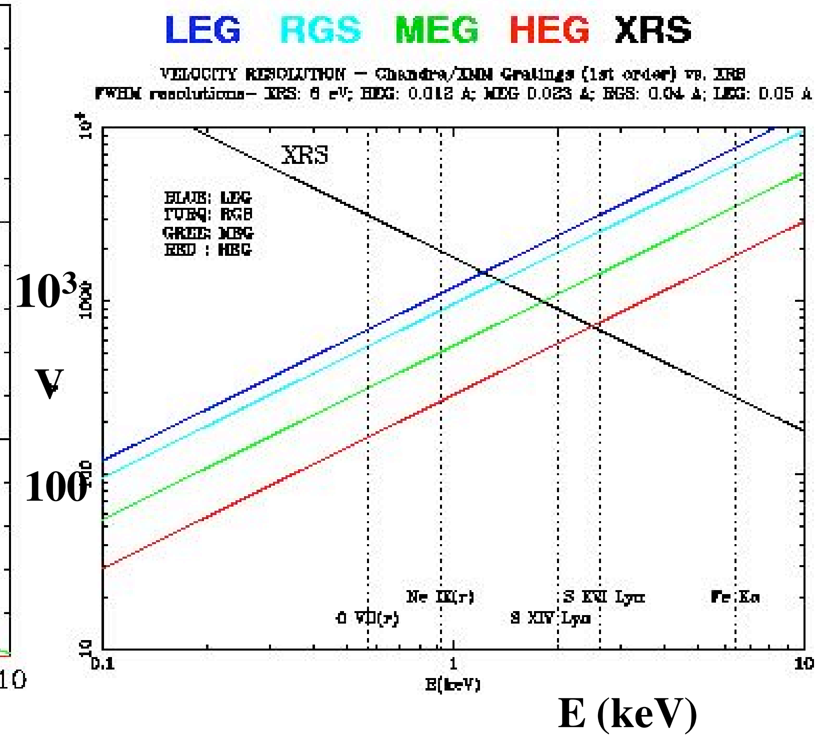
- ❑LETG: ~240 km/s at 0.2 keV [0.16 eV]
- ❑MEG: ~280 km/s at 0.5 keV [0.47 eV]
- ❑RGS: ~290 km/s at 0.3 keV [0.29 eV]

Thermal widths:

FWHM ~ 30 $(52\ T_6\ /A)^{0.5}$ km/s

A = atomic mass

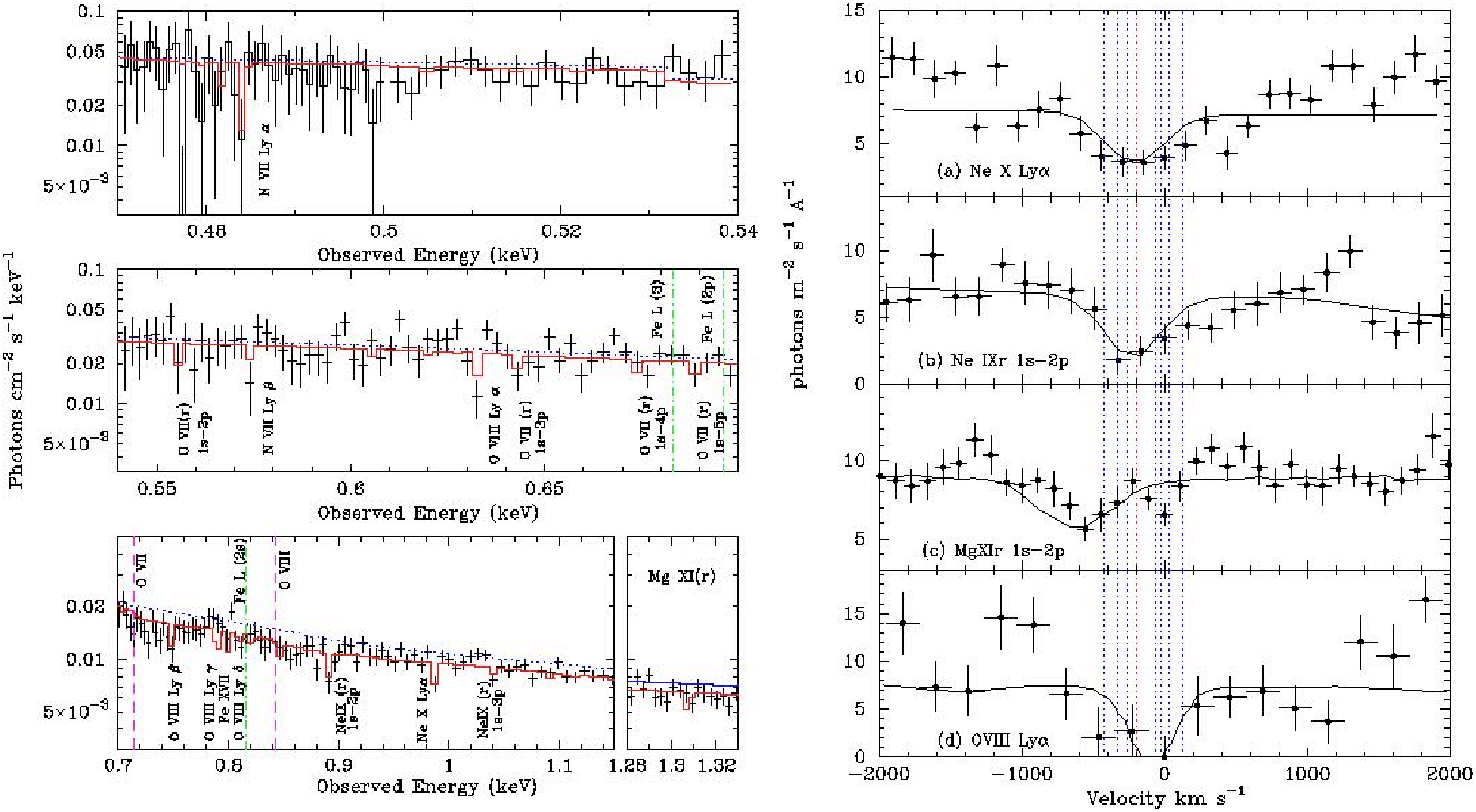




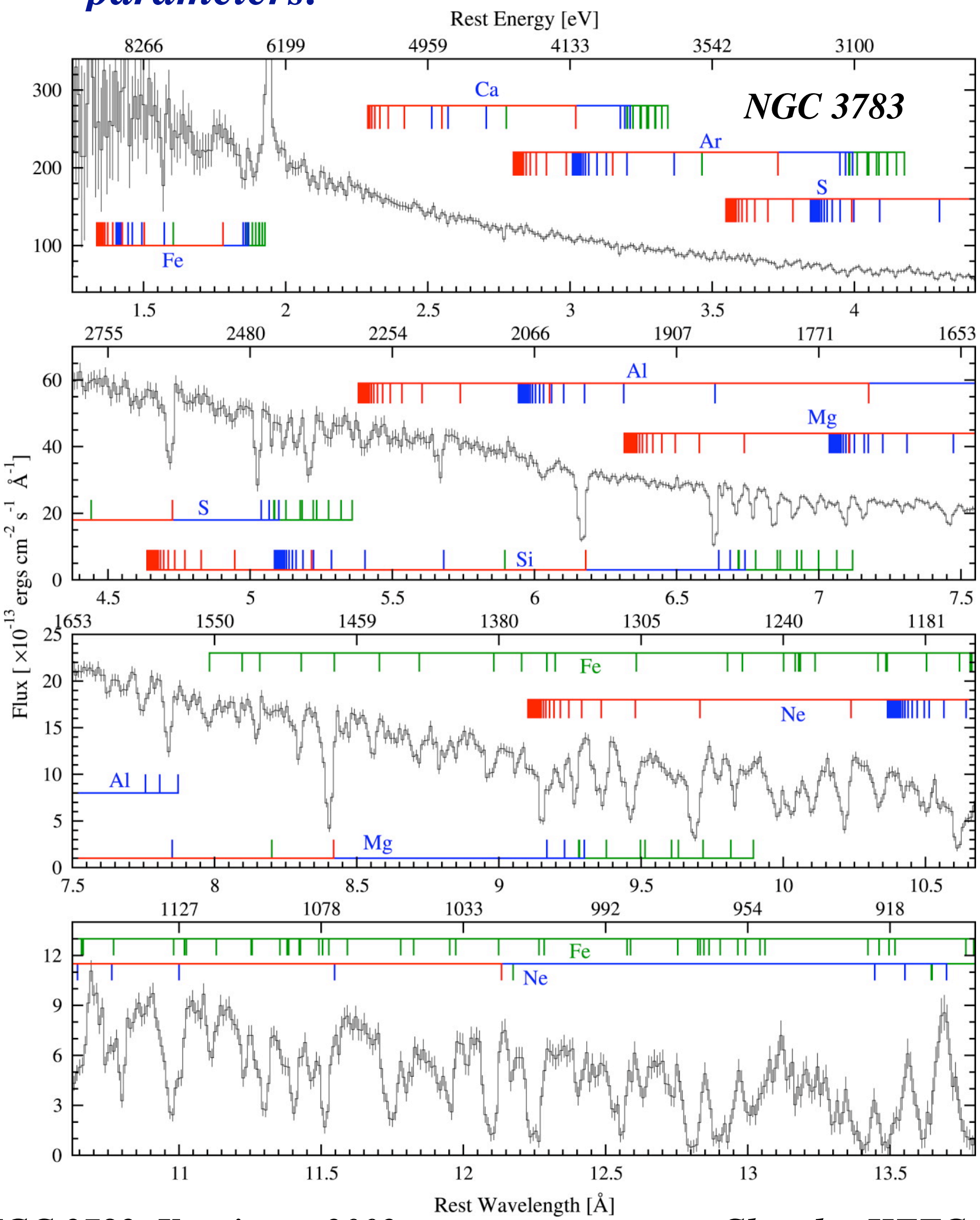
What Do We See?

Mostly He-like, H-like unresolved absorption lines; in most cases blueshifted w.r.t. to systemic (~0-1000 km/s FWHM).

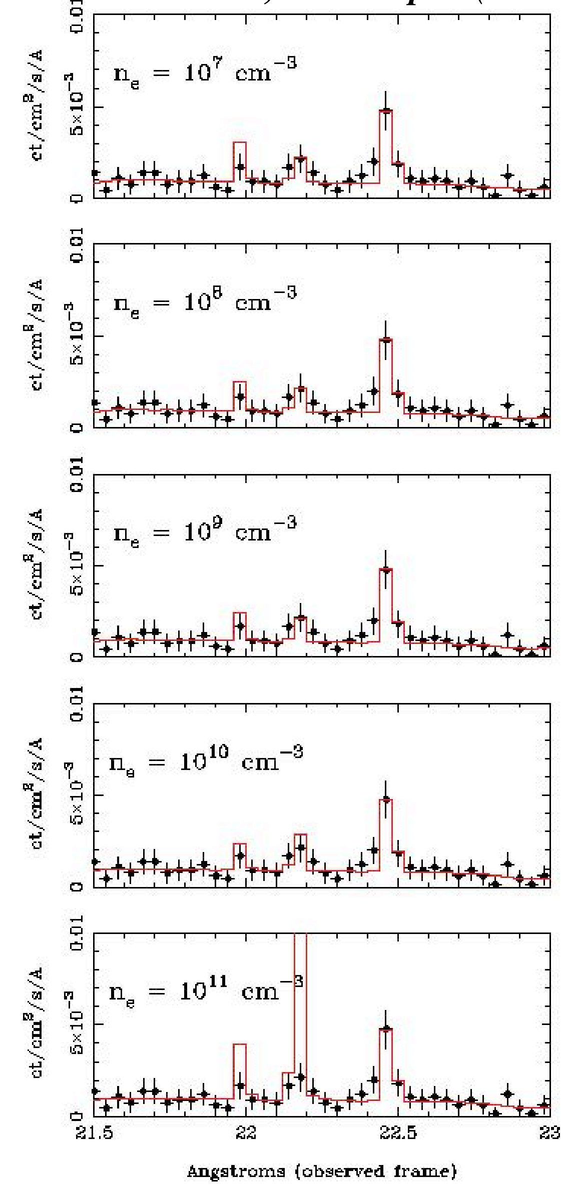
Mkn 509 Chandra HETG+HST STIS campaign [Yaqoob et al. 2003]



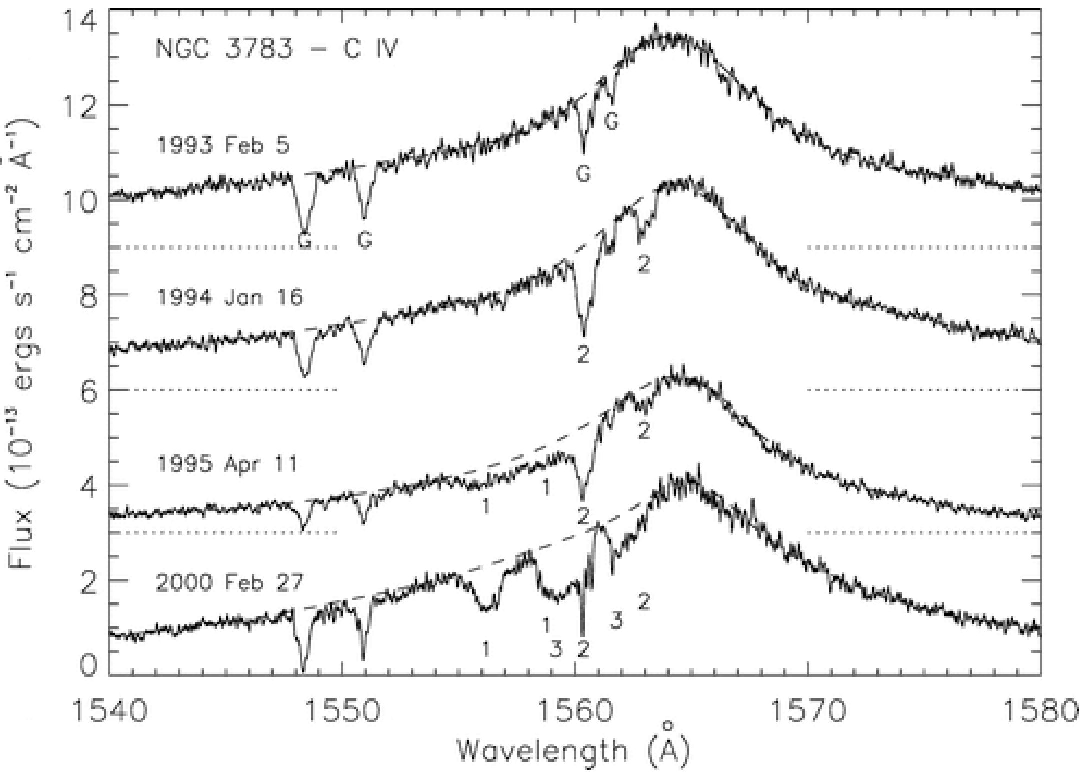
Usually the absorption cannot be modeled by single zone; multiple components required with wide range of ionization states..different columns & ionization parameters.

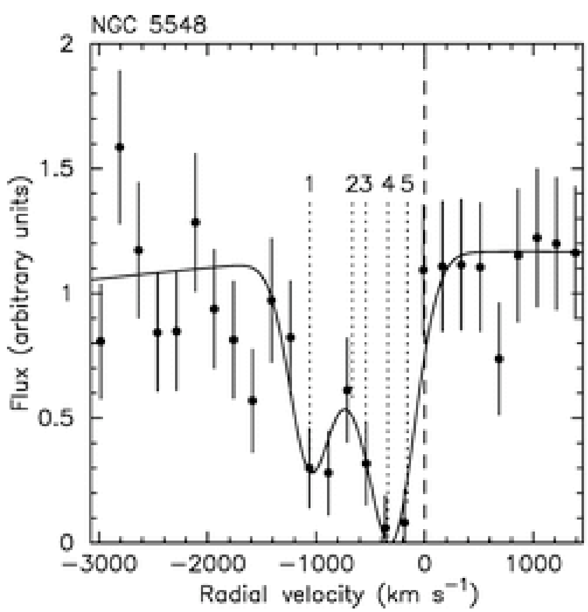


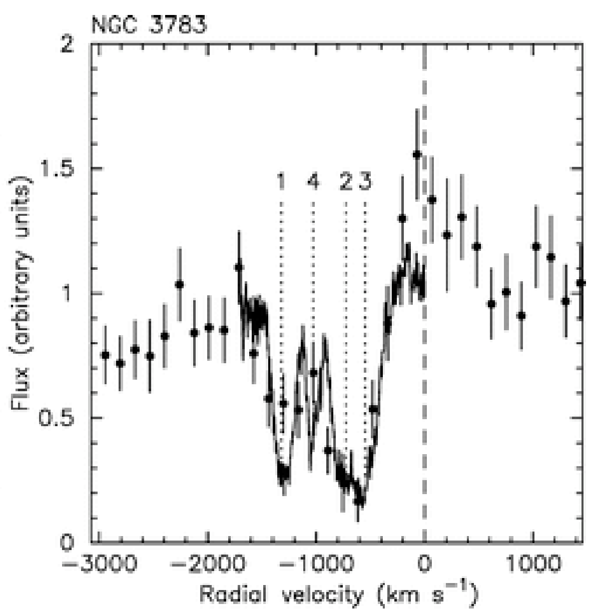
NGC 5548, OVII triplet (MEG)



NGC 3783, Kaspi et a. 2002 *Chandra HETG*



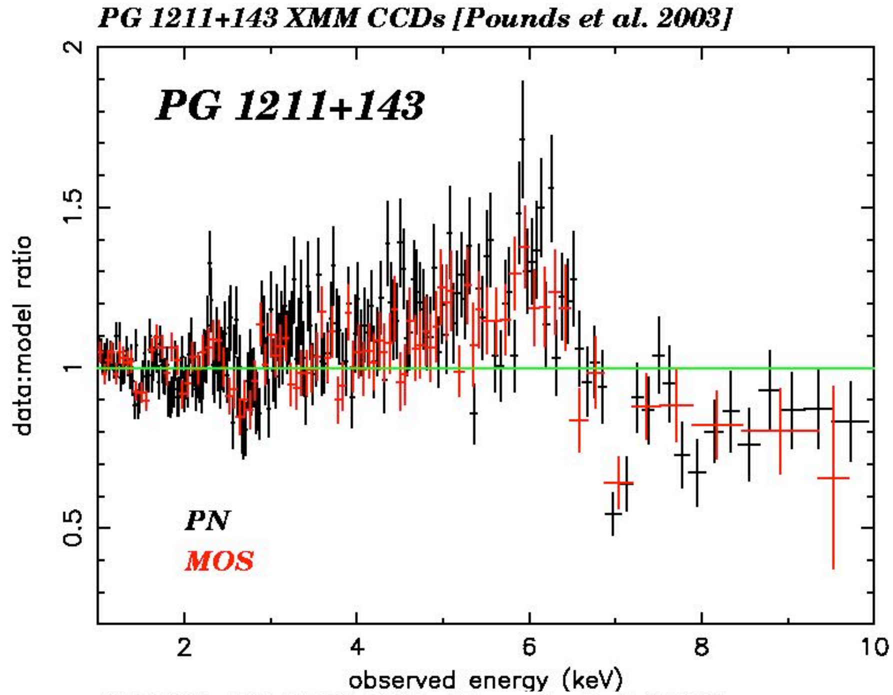


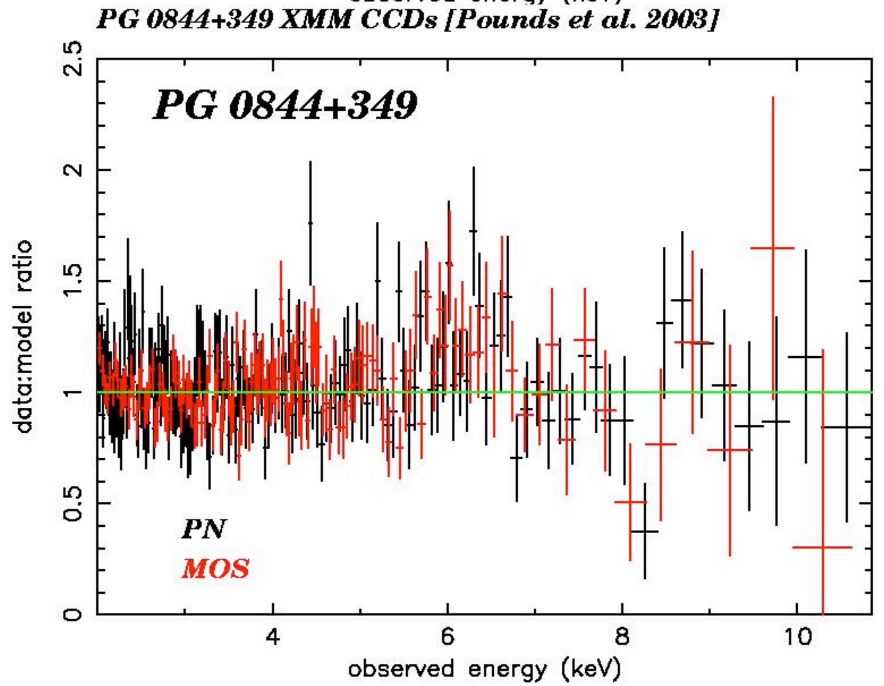


- **X-ray/UV connection**
- **X-ray & UV absorbers share kinematics**
- **Much higher resolution in UV - why discrete components?**
- **Hints of velocity structure in some X-ray profiles, details elusive.**
- **Very different UV & X-ray columns (but e.g. Arav et al. '04: UV columns much larger?).**
- **Two-phase? UV "knots" in an X-ray wind?**

Details of a physical model need to be filled in. Multi-temperature wind (cf. Krolik & Kriss 2001)? What drives it & what is the source of the matter?

From Crenshaw, Kraemer & George 2003, AR&AA, 41, 117





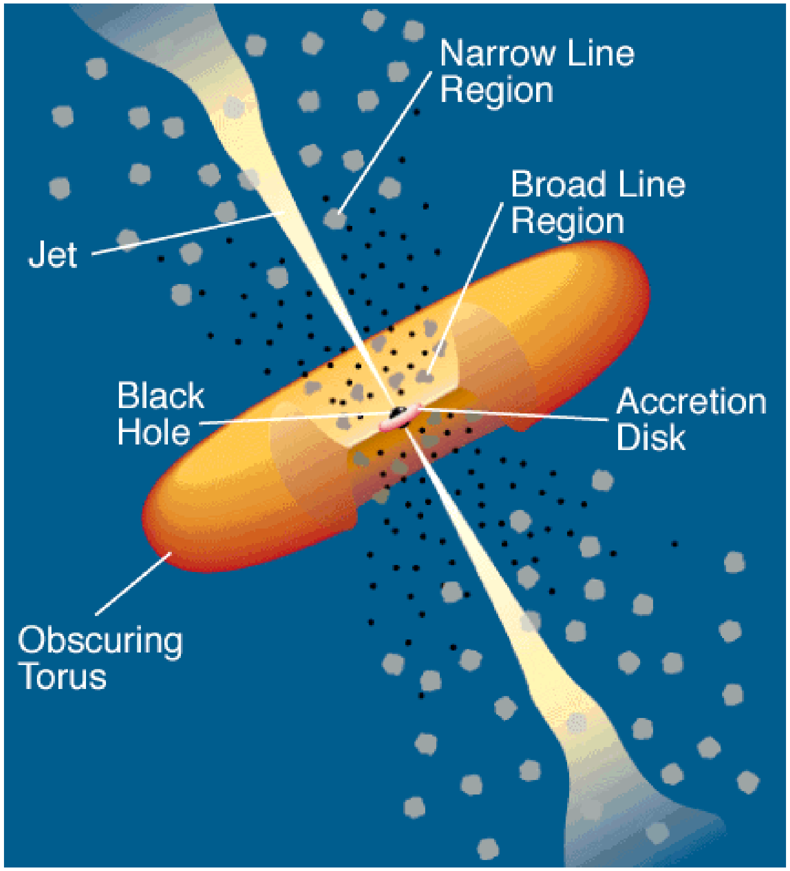
Extreme Outflows

- XMM CCD detections of very high-velocity outflows deduced from (blueshifted) Fe-K absorption lines from highly ionized Fe in some QSOs (Pounds, Reeves et al. 2003..).
- PG 1211+143: v~ 24,000 km/s
- PG 0844+349: v~ 60,000 km/s
- High optical depths: N_H~ 5 x 10^{23} cm^{-2} or more..but model-dependent.
- Other examples: PDS 456 (v~55,000 km/s).
- These are moderately low redshift QSOs (z<0.2).

A Chandra HETG Sample of Seyfert 1 Galaxies

What we want to know:

- **Where does the outflow originate?**
- **What is its size? Geometry?**
- **Physical, thermal, & ionization structure? Kinematics?**
- **Source of material in the wind?**
- **What determines properties of the outflow?**
- **What is the nature of the connection between the outflow and the central black hole plus accretion disk?**
- **Covering factor?**
- **What drives the outflow?**
- **Mass outflow rate (compare to accretion)?**



Urry & Padovani 1995

Test for correlations between outflow properties & other key properties of the central engine.

A Chandra HETG Sample of Seyfert 1 Galaxies

Selection:

- ***Low z (<0.05) Seyfert 1 galaxies***
- ***Public HETG data up to 1 July, 2003***
- ***Bright (HEG > 0.05 ct/s)***
- ***-> 15 AGN; 10/15 exhibit signatures of ionized absorption.***

(Detailed results in McKernan, Yaqoob, Reynolds 2004)

What we can measure:

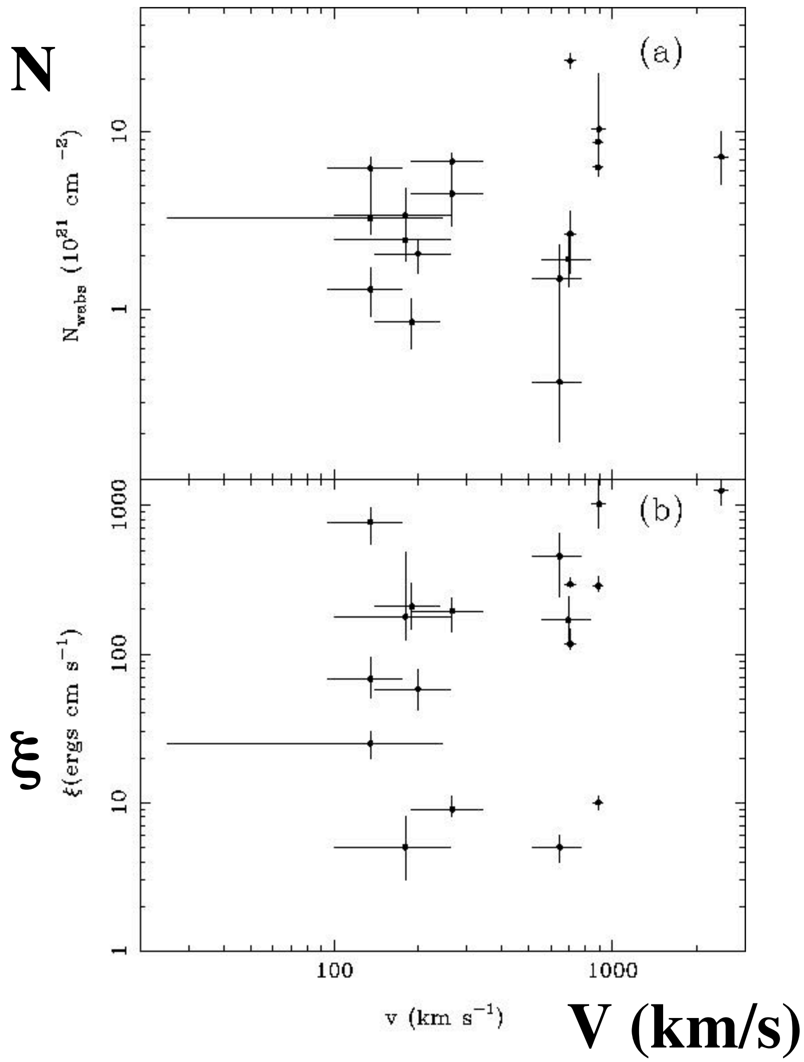
- ***Columns, ionization parameters from modeling; offset velocities of absorption lines; crude kinematic information (widths, profiles).***
- ***If sufficient emission-line data, density. Cannot get distance from center without density or variability information.***
- ***UV absorption: 4 of the 15 have simultaneous UV/Chandra data. How are UV/X-ray columns, ionization parameters, covering factors and kinematics related?***

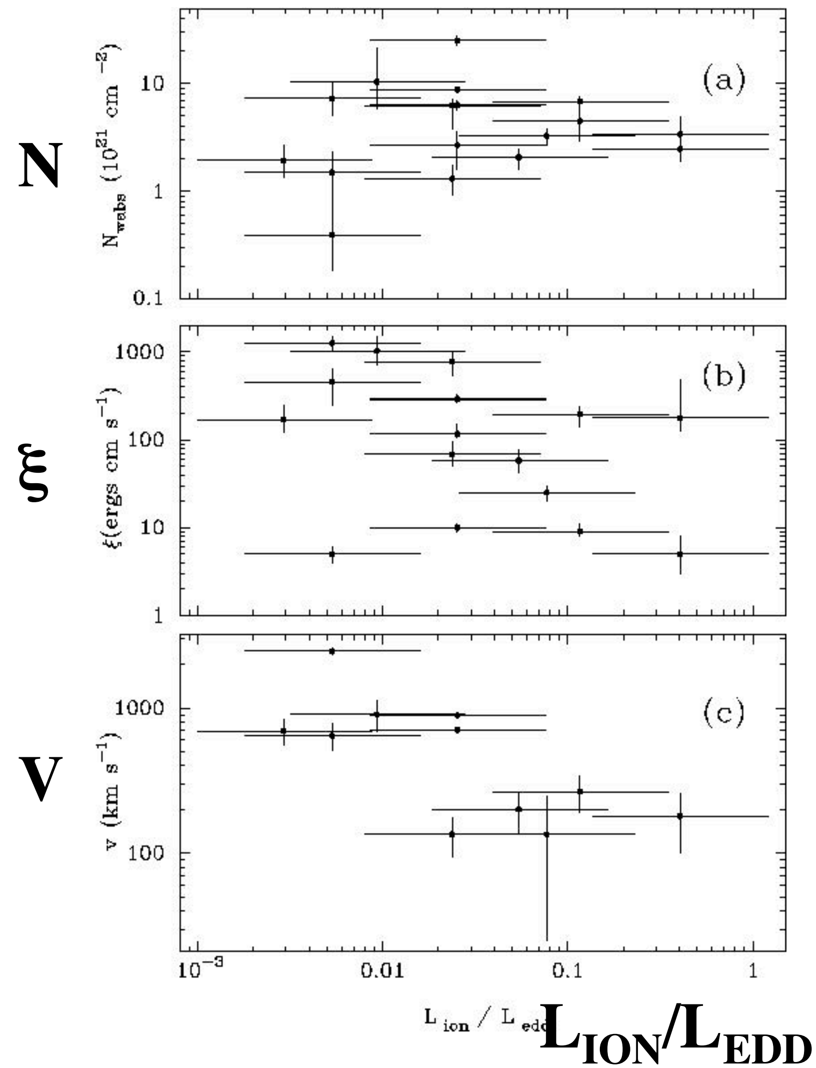
The HETG Seyfert 1 Sample

Source	RA (J2000.0)	Decl. (J2000.0)	Redshift (z)	Galactic N_H (10^{20}cm^{-2}) [a]	Observation Start [b]	Exposure[c] (ks)
Fairall 9	01 23 45.7	-58 48 21	0.04600	3.0	2001 Sep 11	80
3C 120[d]	04 33 11.0	05 21 15	0.03301	12.30	2001 Dec 21	58
NGC 3227	10 23 30.6	+19 51 54	0.00386	2.15	1999 Dec 30	47
NGC 3516	11 06 47.5	+72 34 07	0.00884	3.05	2001 April 9	200
NGC 3783	11 39 01.7	-37 44 18	0.00973	8.50	2001 Feb 24	850
NGC 4051	12 03 09.5	44 31 52	0.00242	1.31	2000 Mar 24	80
Mkn 766	12 18 26.5	29 48 46	0.01293	1.80	2001 May 7	90
NGC 4593	12 39 39.3	-05 20 39	0.00831	1.97	2001 Jun 29	79
MCG-6-30-15	13 35 53.3	-34 17 48	0.00775	4.06	2000 Apr 5	126
IC 4329a	13 49 19.2	-30 18 34	0.01605	4.55	2001 Aug 26	60
Mkn 279	13 53 03.5	+69 18 30	0.03045	1.64	2002 May 18	116
NGC 5548	14 17 59.5	25 08 12	0.01717	1.70	2000 Feb 5	82
Mkn 509	20 44 09.6	-10 43 23	0.03440	4.44	2001 Apr 13	60
NGC 7314	22 35 46.2	-26 03 01	0.00474	1.46	2002 Jul 19	97
Akn 564	22 42 39.3	29 43 31	0.02467	6.40	2000 Jun 17	50

Correlations with Outflow Velocity & L_{ION}/L_{EDD}

McKernan, Yaqoob, & Reynolds 2004

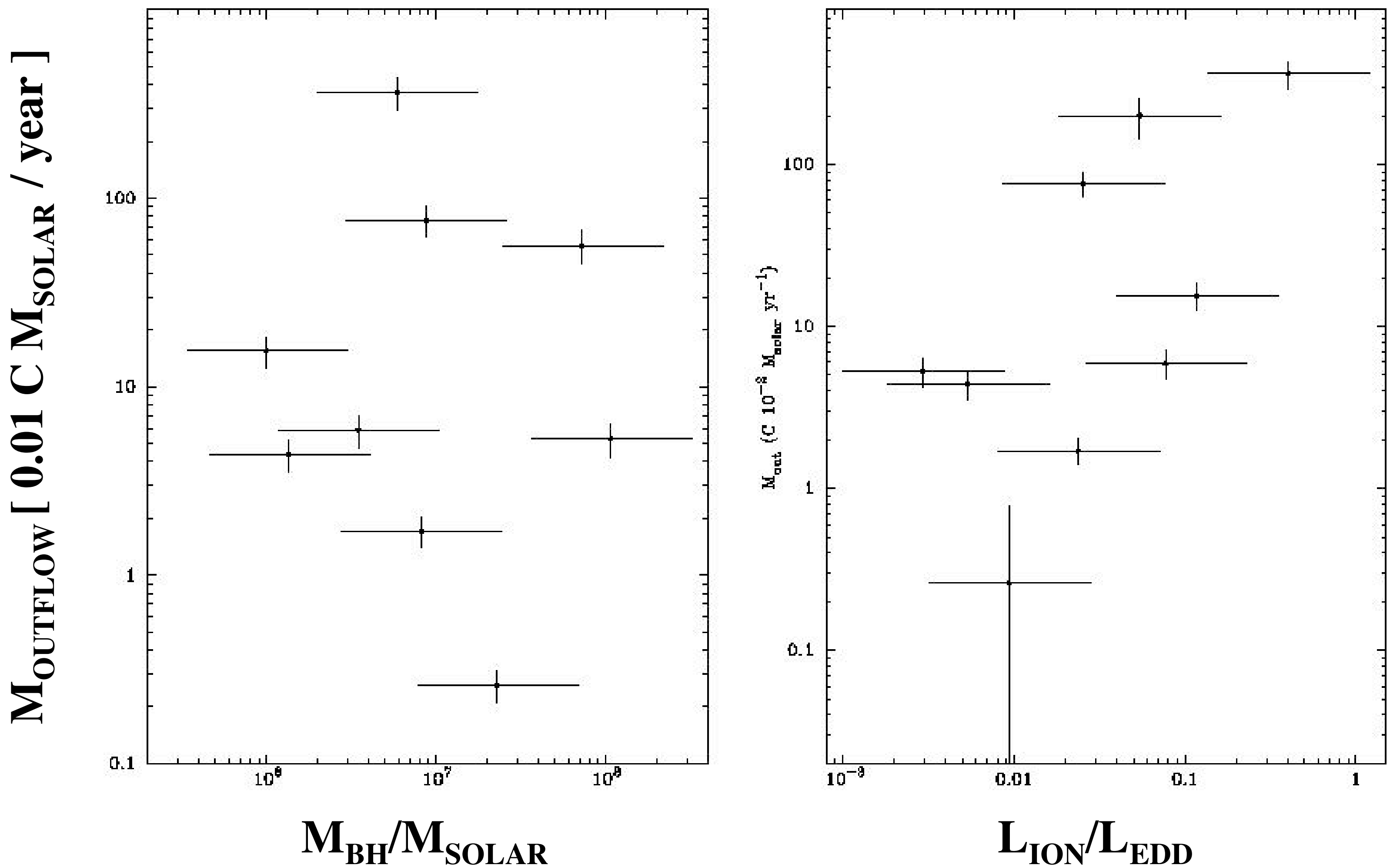




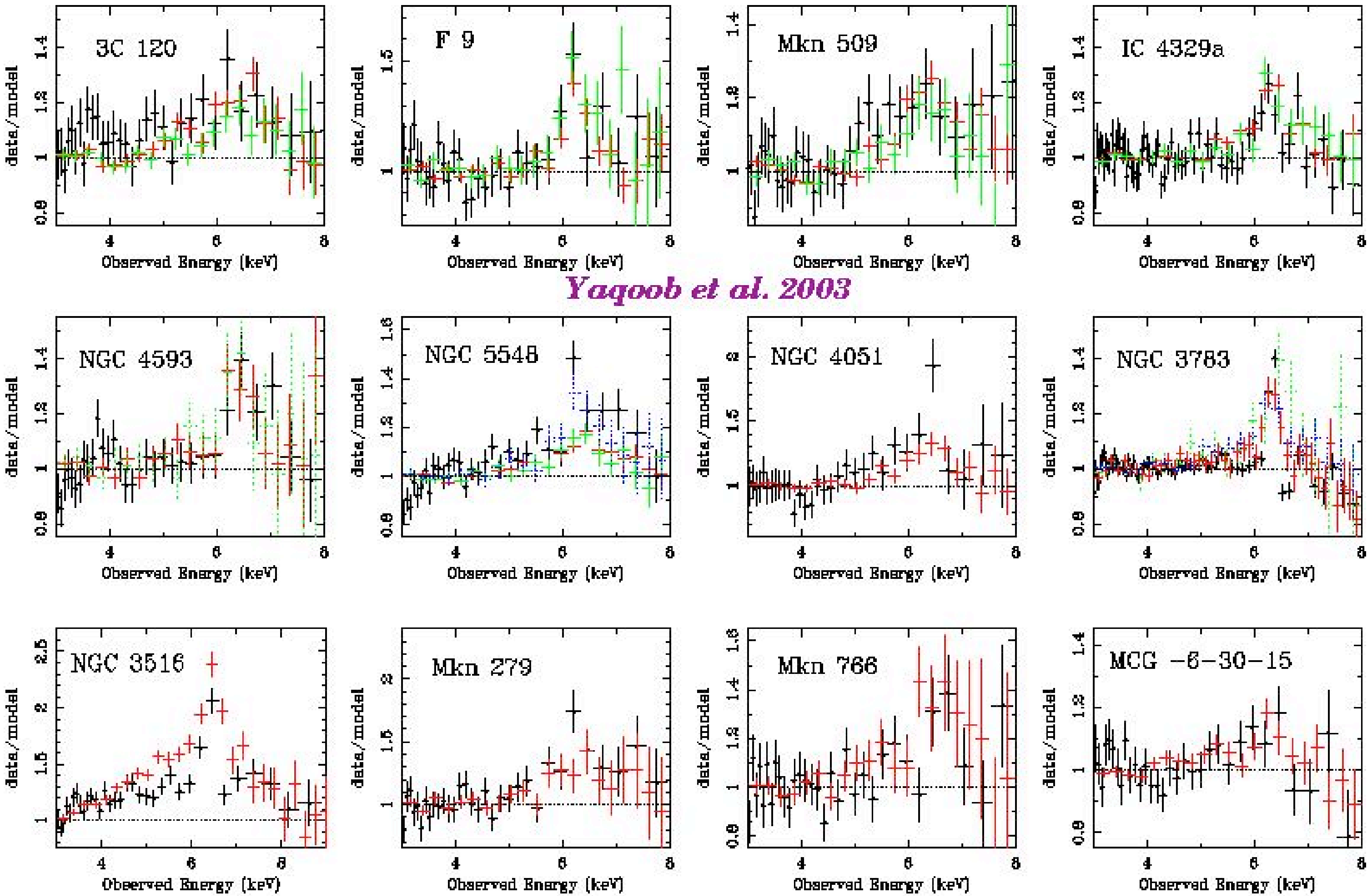
- *V appears to have a bimodal distribution. Anti-correlated with L_{ION}/L_{EDD}?*
- *No correlation of N with L_{ION}/L_{EDD}. Possible anti-correlation of ξ with L_{ION}/L_{EDD}.*

Correlations with Black Hole Mass & L_{ION}/L_{EDD}

McKernan, Yaqoob, & Reynolds 2004

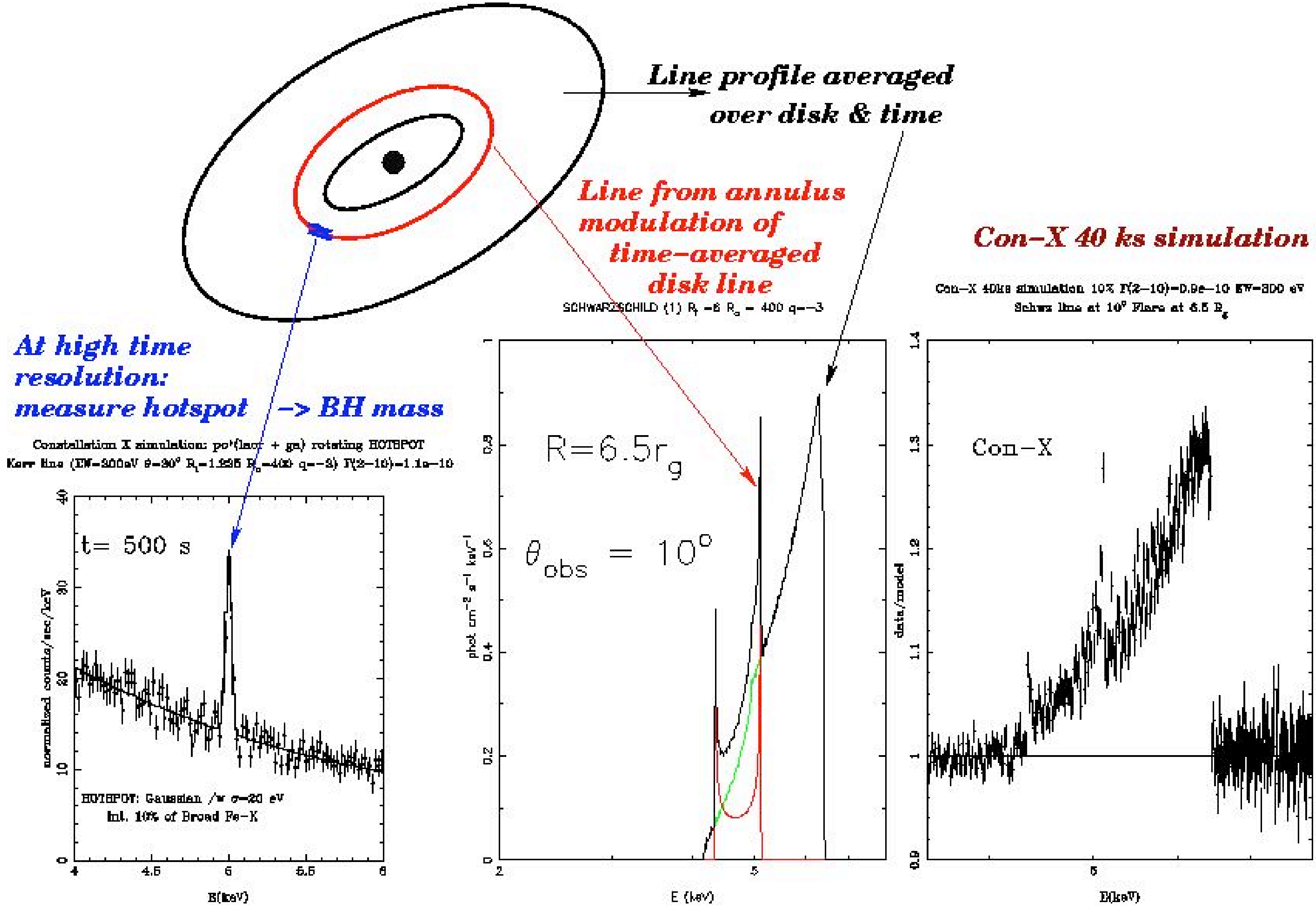


- ***Appears to be no correlation between mass outflow rate and black-hole mass.***
- ***Possible correlation of mass outflow rate with L_{ION}/L_{EDD}.***



Chandra HEG (BLACK) vs. ASCA S0+S1 (COLORED)

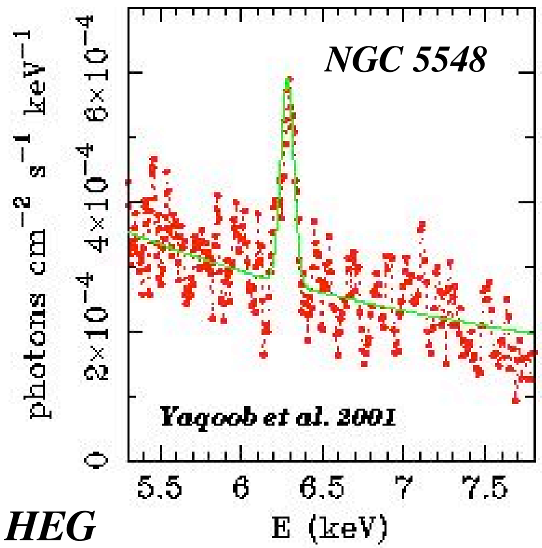
Constellation–X Simulations



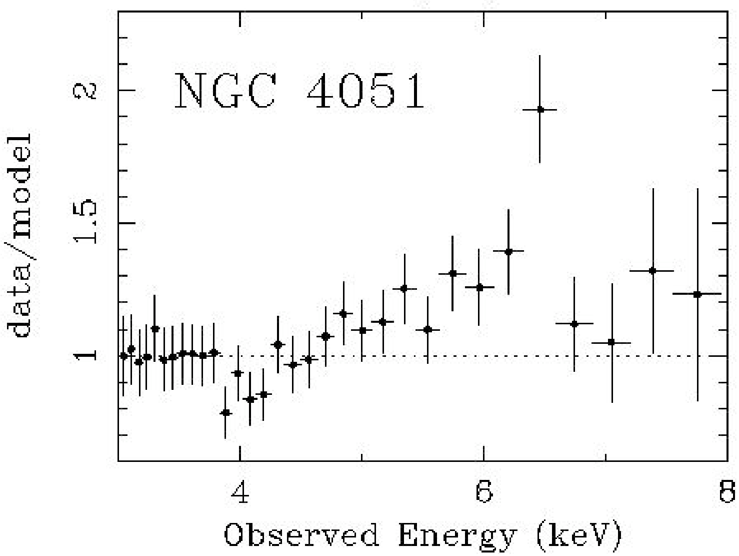
Yaqoob 2000–2003

Complex Fe-K Emission Lines

HEG Fe–K line at 6.4 keV
FWHM ~4500 km/s, unresolved



HEG



Narrow Fe K line could be from Torus, BLR, NLR

Or is it from a disk emitting at large radii from BH?

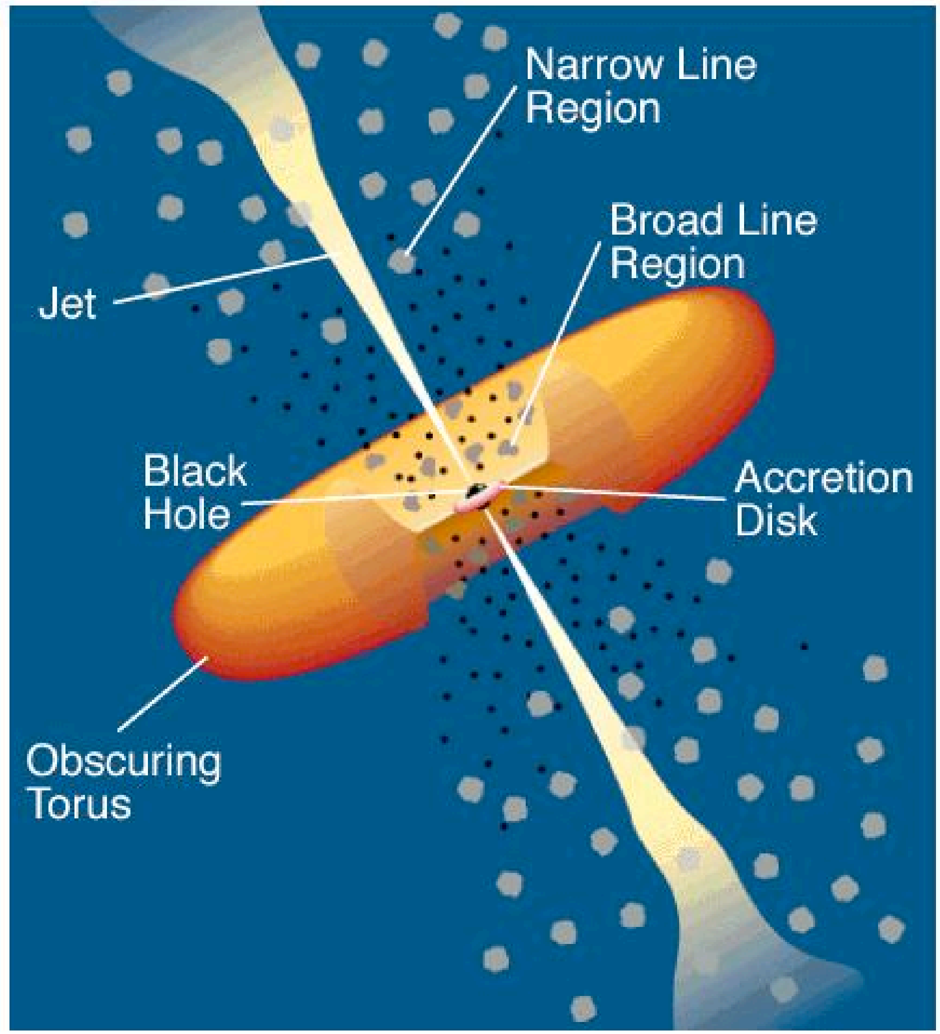
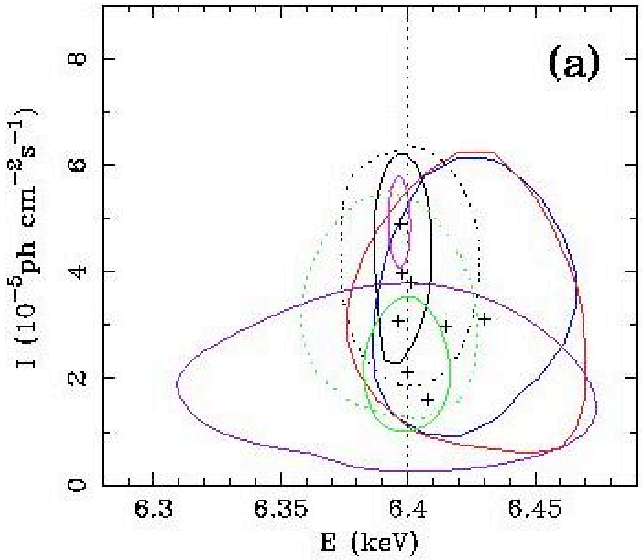


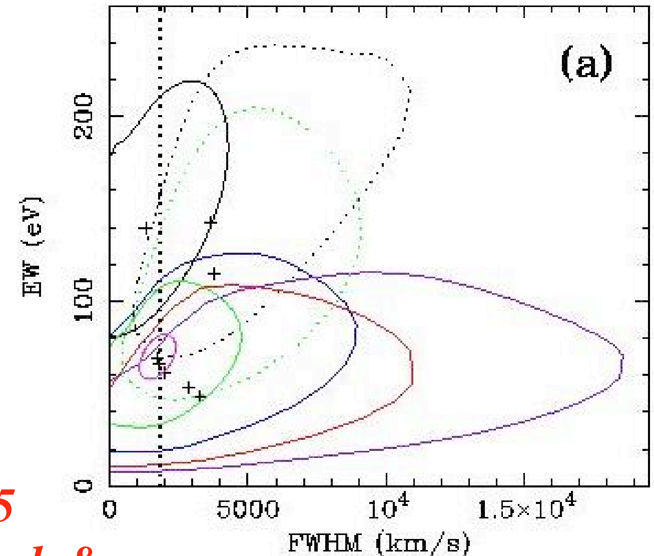
Figure: Urry & Padovani 1995

Peak Energy & FWHM of Fe-K Line Core

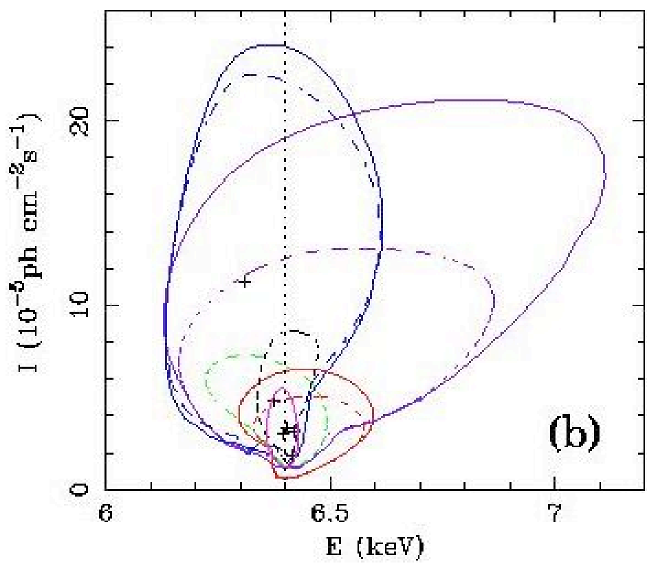


Mean peak energy: 6.404 +/- 0.005 keV

HEG resolution is ~1800 km/s FWHM.

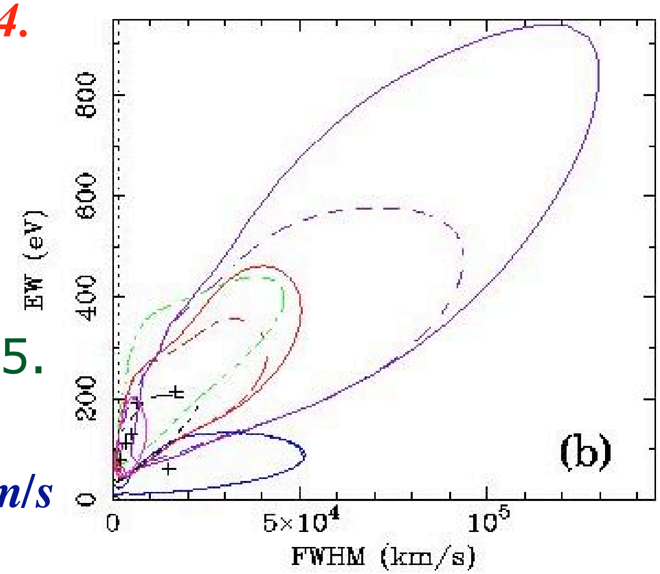


HETG sample of 15 Sy 1 galaxies. Yaqoob & Padmanabhan 2004.

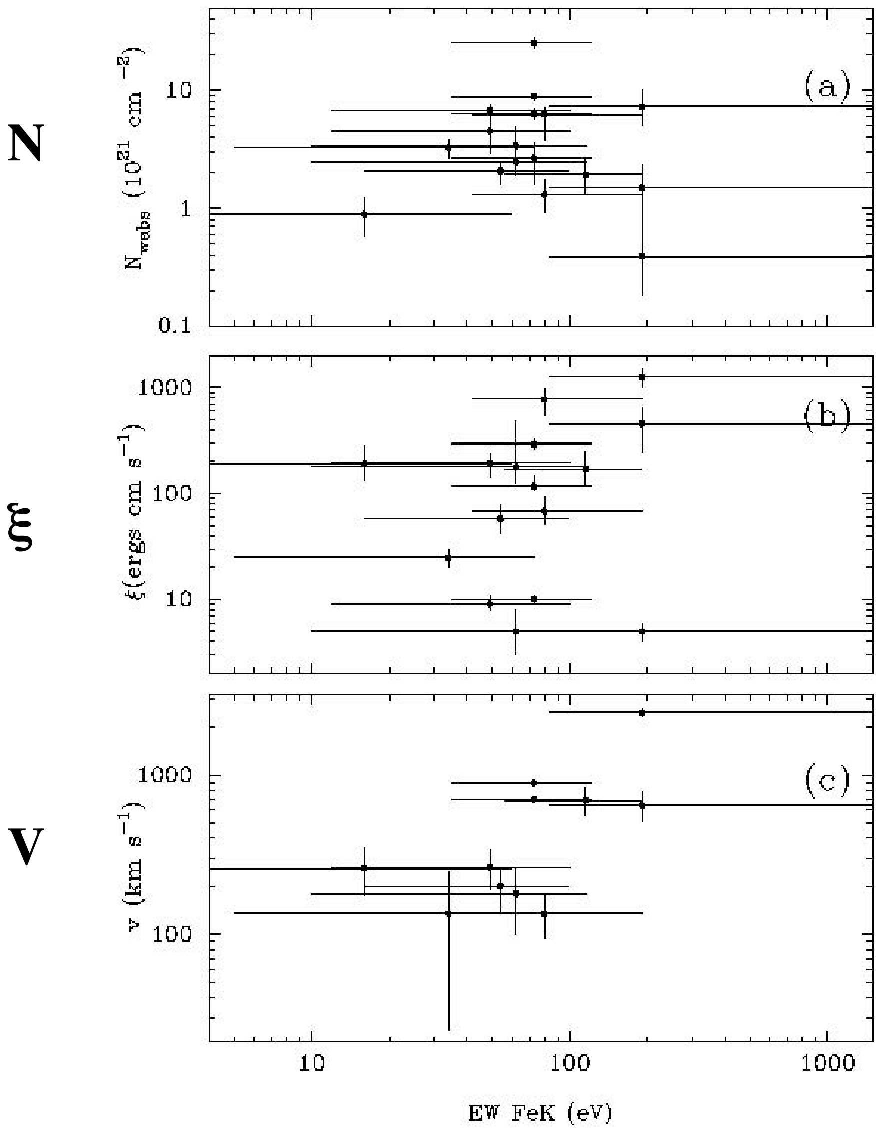


At least 8/15 have a broad line. Core resolved in 3/15.

Mean FWHM: 2380 +/- 760 km/s



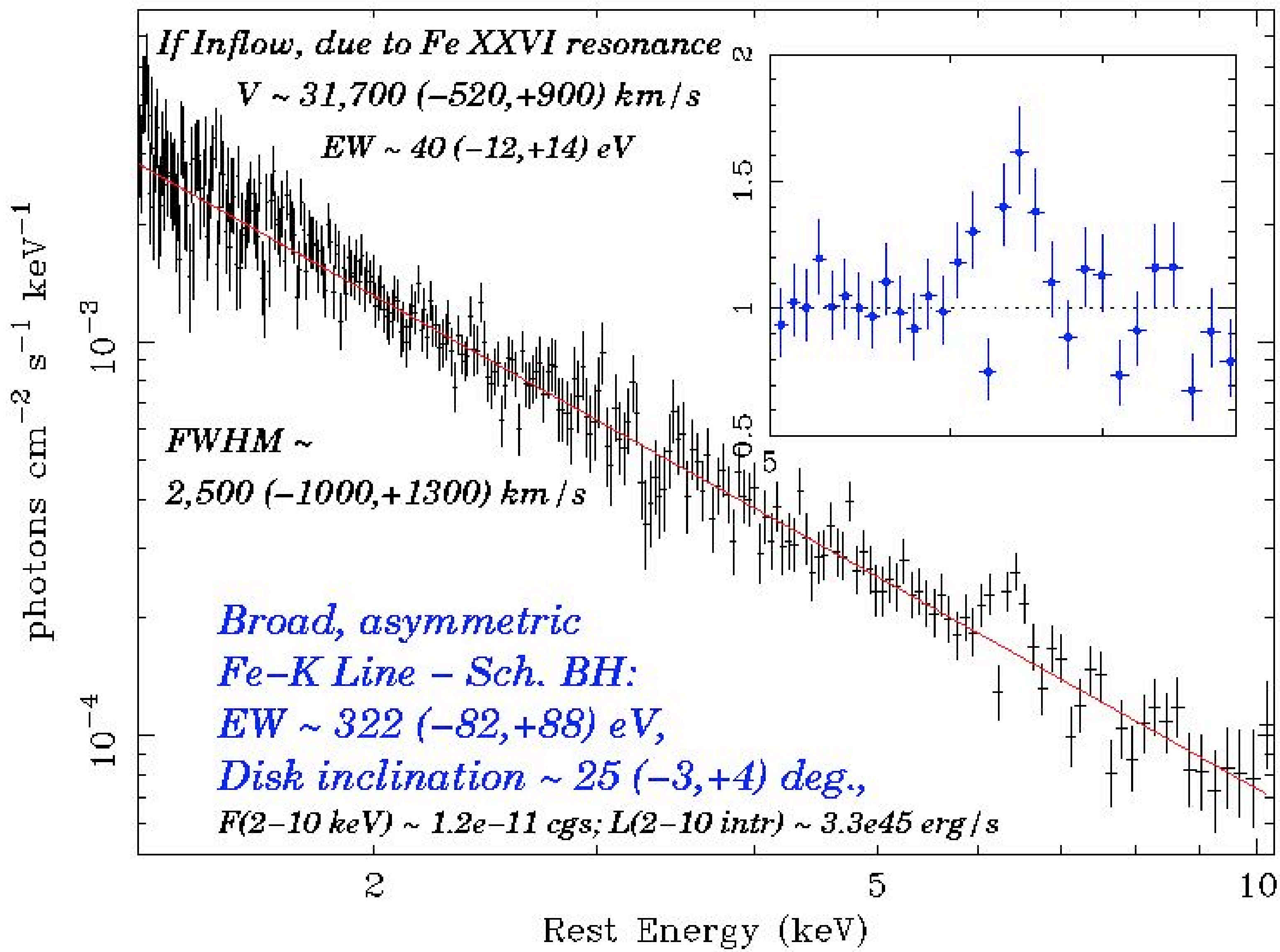
Correlation of Ionized Outflow Parameters with the EW of the Fe-K Line Core



HETG sample of 15 Sy 1 galaxies: Fe-K core EW from Yaqoob & Padmanabhan 2004.

Warm absorber (outflow) parameters from McKernan, Yaqoob & Reynolds (2004).

E 1821+643 (z=0.297 quasar): Redshifted Absorption Line



Yaqoob 2003

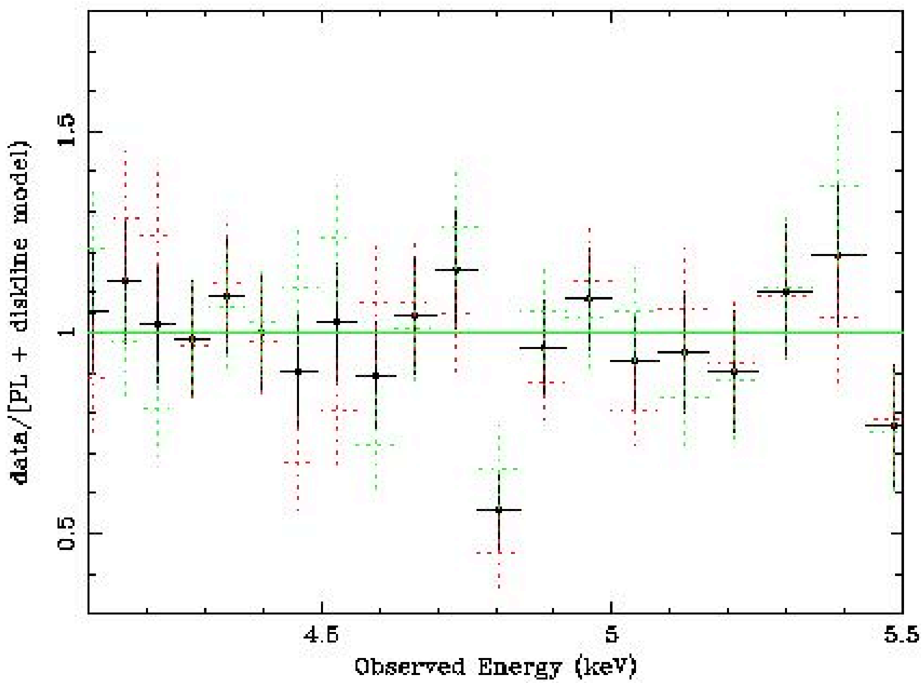
E 1821+643 : Fe–K Absoprtion Feature

Reality of the Absorption Feature

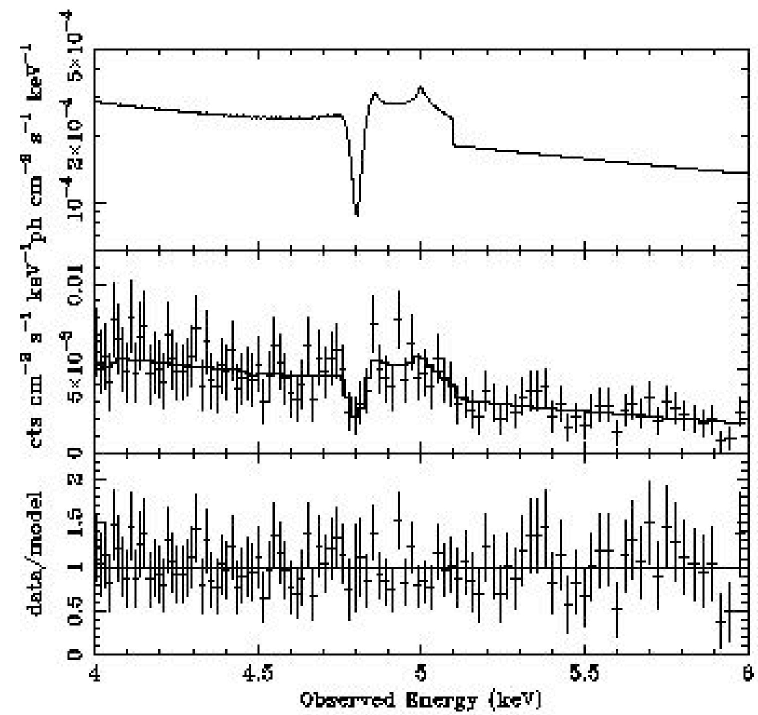
Absorption feature is present in BOTH plus and minus arms of the Chandra High Energy Grating (HEG).

Black: Combined plus & minus orders

Red: –1 Order ***Green: +1 Order***



Disk Emission Line Plus Gaussian Absorption Line Fit.

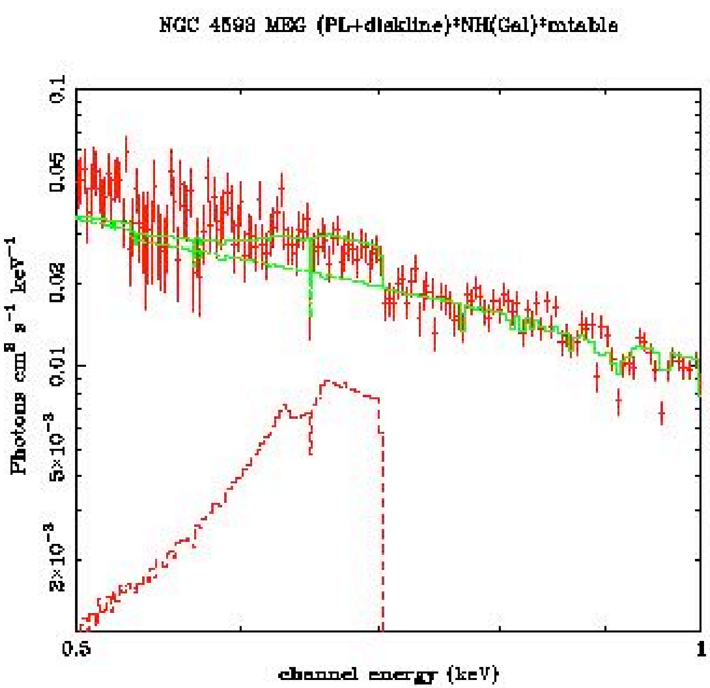


Yaqoob 2003

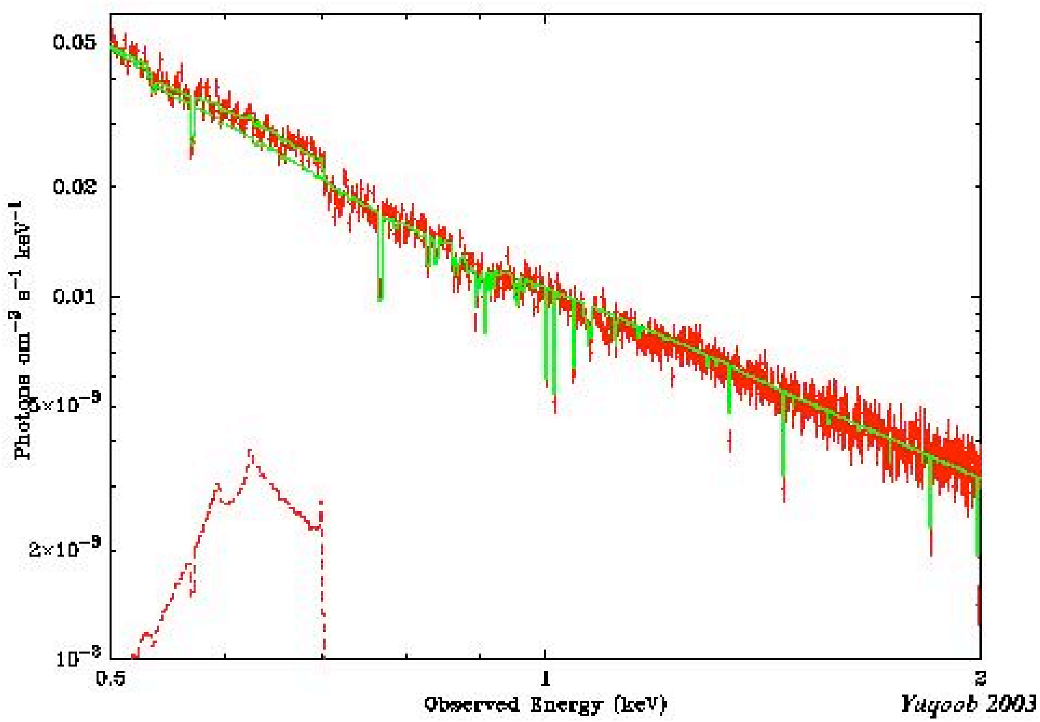
Relativistic Soft X–ray Lines

Astro-E2 is not likely to settle the debate of soft X-ray relativistic lines versus "dust model". Gratings with higher throughput than currently available are likely to solve this problem, rather than calorimeters.

NGC 4593 –Chandra HEG
OVII line plus warm absorber fit.
Disk inclination: 38.7 [–1.0,+0.9] deg.
Edge model gives Eo=0.708 keV.
Statistical errors on Eo only a few eV.



XRS simulation of NGC 4593. Warm absorber plus Fe–L model fitted by warms absorber plus disk line model. Exposure 100 ks. F(2–10) = 4e–11 cgs.

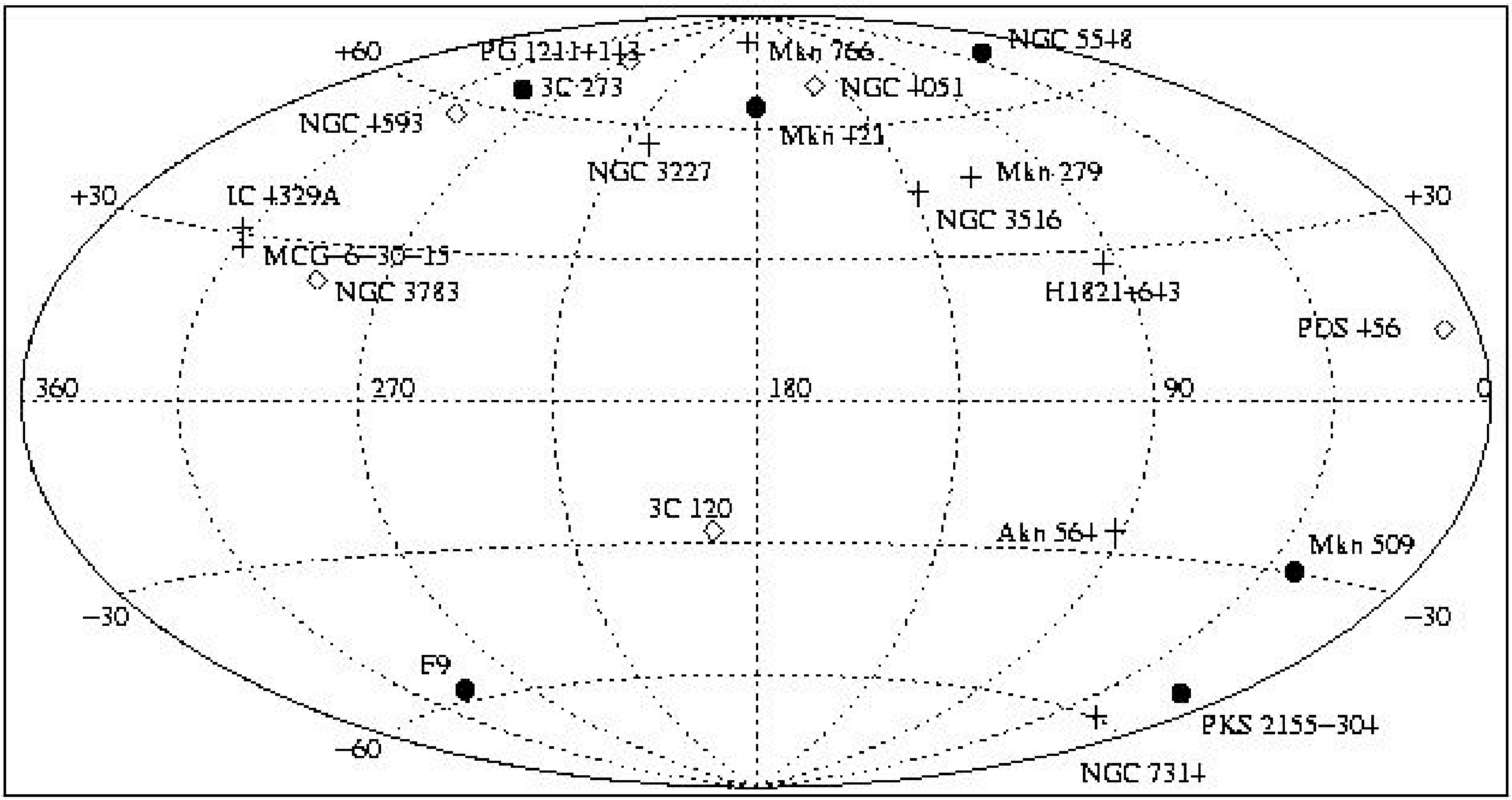


Search for local (z~0) OVII & OVIII Absorption in the HETG AGN sample

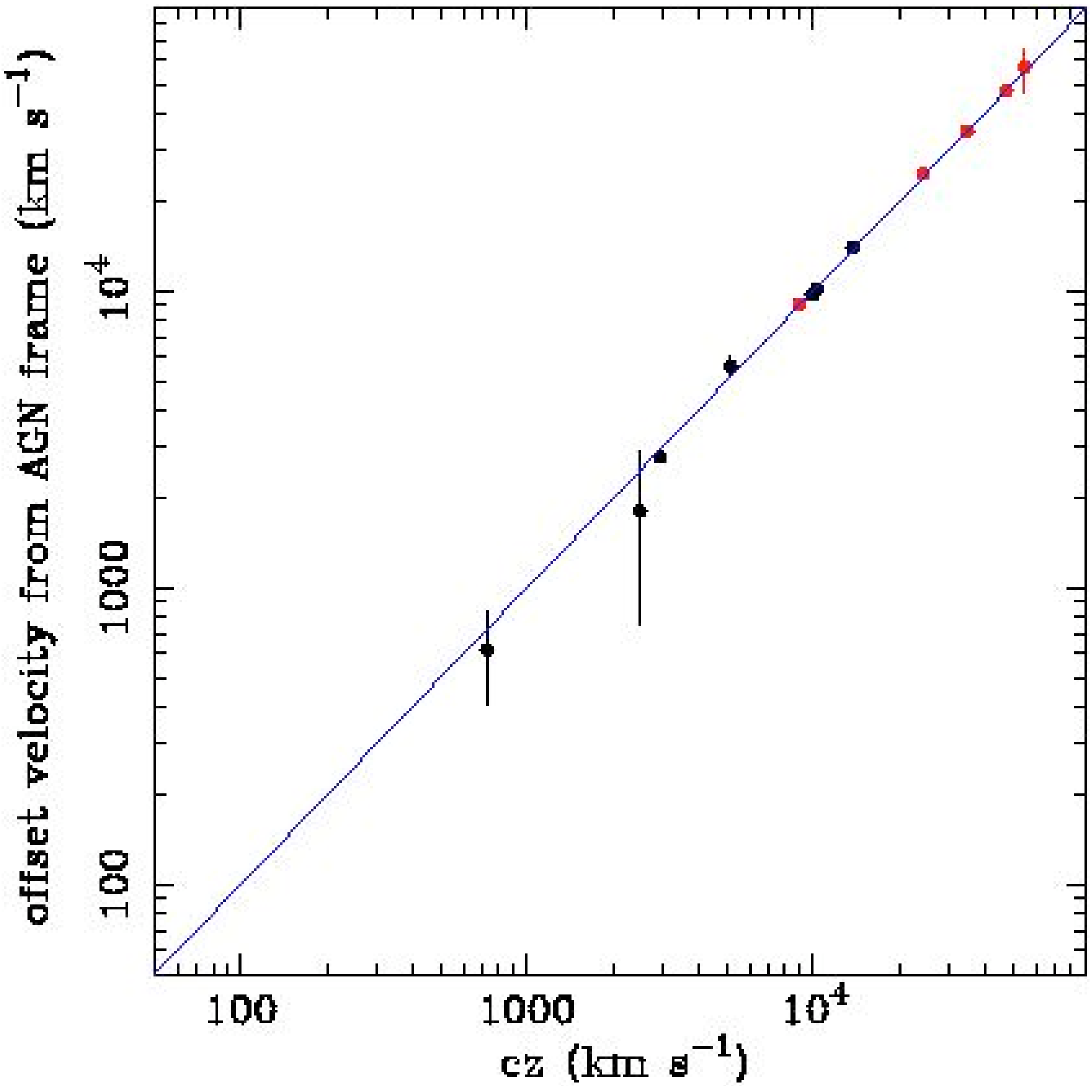
Search for WHIGM in the HETG AGN sample: McKernan, Yaqoob, & Reynolds (2004).

+ No whigm detected; ◇ Ovii & Oviii detected but no FUSE observations;

• Ovii & Oviii detected AND Ovi detected with FUSE.



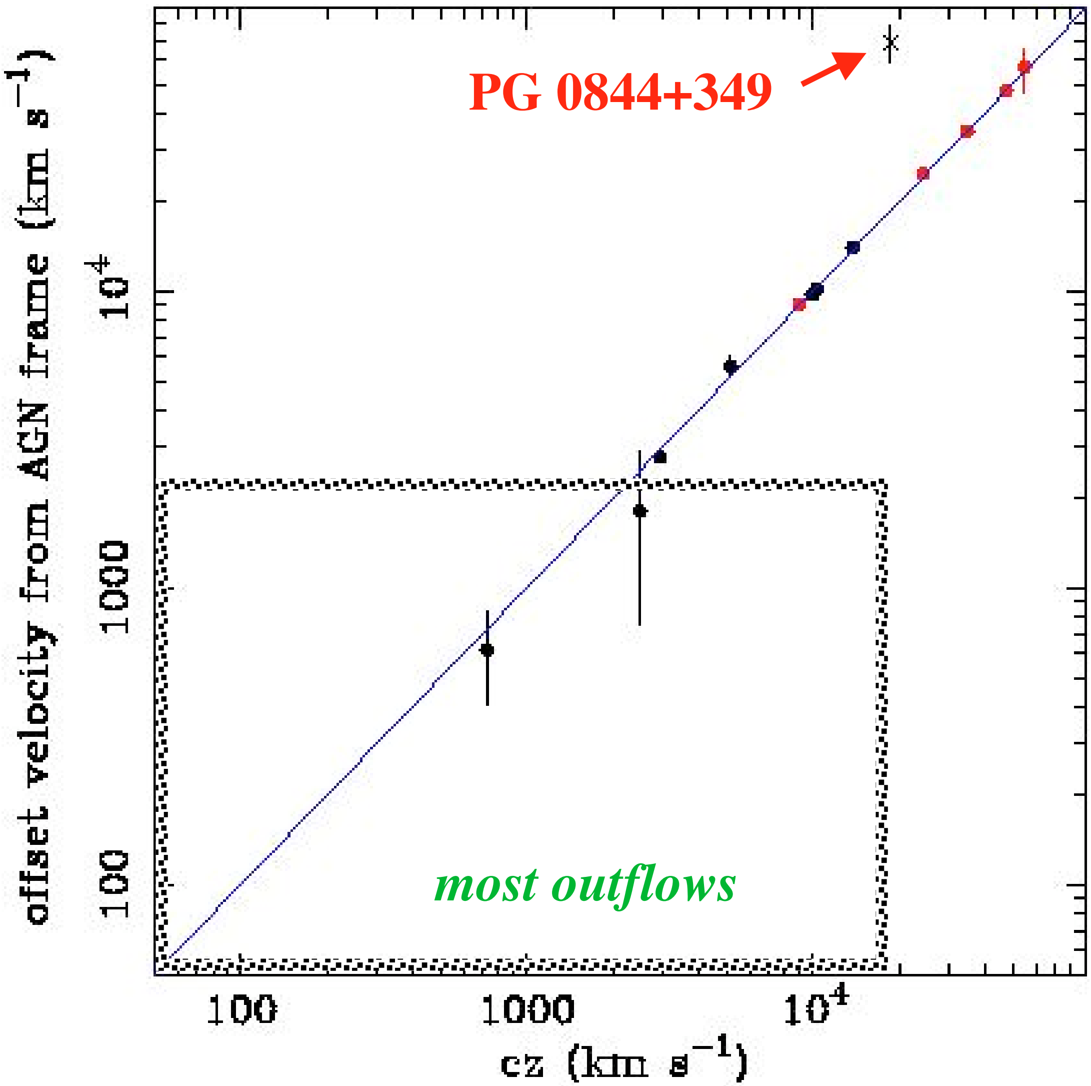
Are the Extreme Outflows Due to WHIGM?



- **Local (z~0) OVII absorption from HETG Seyfert 1.**
- **PDS 456**
  3C 273
  PKS 2155
  PG 1211+143
  Mkn 421

- ***Outflows not claimed in 3C 273, PKS 2155, & Mkn 421.***
- ***"Outflow" in NGC 4051 with V ~ 600 km/s may be due to local absorption.***
- ***Large columns in PG1211+143 & PDS456 make WHIGM interp. very difficult.***

Are the Extreme Outflows Due to WHIGM?



- **Local (z~0) OVII absorption from HETG Seyfert 1.**
- **PDS 456**
  3C 273
  PKS 2155
  PG 1211+143
  Mkn 421

PG 0844+349 does NOT fit on the correlation. The outflow velocity required (from modeling XMM data-Pounds et al. 2004), is ~60,000 km/s, much larger than cz~20,000 km/s.

Summary

- **Origin & location of ionized ouflows *still* unknown.**
- **Sub-eV resolution is *required*. Most absorption lines would still be unresolved.**
- **X-ray columns ~$10^{21\text{-}22}$ cm^{-2}, ξ ~ $10^{1\text{-}3}$, sometimes in same source.**
- **Location, N_e, X-ray covering factor (C) *require* variability studies. Only possible with large effective area gratings. (*Chandra* monitoring of NGC 3783 gave only crude lower limit on R, ~ pc scale. Origin may still be at accretion disk, but *detection* may only be possible for matter further out).**
- **Can only measure absolute mass outflow rate when C is known. If C is similar in different AGN, we find a tentative connection between mass flow and accretion efficiency. For large covering factors, mass outflow rate comparable to accretion rate (~0.01-0.1 solar masses/year).**
- **Tentative connection between ouflow velocity and accretion efficiency, independent of C. Bimodal V?**
- **Some very high V outflows in QSOs may be really be due to z~ 0, local absorption (whigm?). However, the implied column density for whigm is way too high.**